ARPA ORDER NO. 91-5

A RAND REPORT

PREPARED FOR

ADVANCED RESEARCH PROJECTS AGENCY

DEPARTMENT OF DEFENSE

This research is supported and monitored by the Advanced Research Projects Agency under Contract No. AF 49(638)-710. This report does not necessarily represent the views of the Advanced Research Projects Agency.

The RAND Corporation
SANTA MONICA • CALIFORNIA

RAND RESEARCH MEMORANDUM

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS

A. L. Latter

RM-2659-ARPA November 2, 1960

in brief

In October of 1960, the VELA Technical Symposium convened in Washington, D.C., where this research memorandum was presented. The symposium was held to investigate some problems and potential solutions for detecting underground nuclear tests.

The author discusses implications of, and questions raised by, the "Cowboy" underground detonations with chemical explosives conducted in Louisiana one year ago. These experiments verified the correctness of the theory that explosions in a large cavity experience a "decoupling" effect, that is, the resulting seismic signals are muffled.

The Cowboy tests left certain problems still to be solved. For example, the minimum cavity volume for full decoupling is based on the requirement that the average explosion pressure must not exceed one-half the overburden pressure. This requirement is probably too stringent, particularly for nuclear explosions, but experiments are needed with decoupled nuclear shots to obtain a better estimate. Since Cowboy shows that decoupling is not an all or none effect, it appears desirable to obtain the decoupling factor as a function of cavity volume, even when the latter is too small to ensure elasticity of the medium. Cowboy provides information about this curve for chemical explosions, but nuclear explosions may be different. Cowboy was conducted at a shallow depth where plasticity is unimportant. Cavities at greater depth will involve this new phenomenon, which may make the decoupling factor bigger.

The RAND Corporation
1700 Main St. • Santa Monica • California

ARPA ORDER NO. 9

A RAND REPORT

PREPARED FOR

ADVANCED RESEARCH PROJECTS AGENCY

DEPARTMENT OF DEFENSE

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS

Albert L. Latter

RM-2659-ARPA

November 2, 1960

This research is supported and monitored by the Advanced Research Projects Agency under Contract No. AF 49(638)-710. This report does not necessarily represent the views of the Advanced Research Projects Agency.

The RAND Corporation

1700 MAIN ST. • SANTA MONICA • CALIFORNIA

PREFACE

This report was prepared for the VELA Technical Symposium held in Washington October 4 and 5, 1960.

By way of background the word ''decoupling'' refers to any method, particularly the use of a large cavity, for reducing the seismic signal from underground explosions. Cowboy is the name of the series of experiments conducted in December 1959 and January 1960 with chemical explosives fully tamped and in cavities located in a salt dome medium in Louisiana.

SUMMARY

The Cowboy experiments showed that the principle of big-hole decoupling is correct. However the decoupling factor is not known precisely. The best guess is still 300 for a hole in salt relative to a tamped shot in tuff, but this value is uncertain by a factor of 2 or 3. The minimum cavity volume for full decoupling is based on the requirement, derived theoretically, that the average explosion pressure must not exceed one-half the overburden pressure. This requirement is probably too stringent, particularly for nuclear explosions, but experiments are needed with decoupled nuclear shots to obtain a better estimate. Since Cowboy has shown that decoupling is not an all-or-none effect, it would be desirable to obtain the decoupling factor as a function of cavity volume, even when the latter is too small to ensure elasticity of the medium. Cowboy gave some information about this curve for chemical explosions, but nuclear explosions could be different. Also Cowboy was conducted at a shallow depth where plasticity is unimportant. Cavities at greater depth will involve this new phenomenon, which may make the decoupling factor bigger.

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS

After Cowboy, what questions remain about the big-hole method of decoupling? I think there is no doubt that the decoupling principle is correct. The seismic signal can be reduced by more than two orders of magnitude with a sufficiently large hole, where ''sufficiently large'' means the average explosion pressure does not exceed something in the neighborhood of the overburden pressure.

A question arises, however, if we want to have a more precise value of the decoupling factor. Prior to Cowboy, we predicted, on the basis of elasticity theory for the hole and measurements of earth displacement and seismic energy on the Rainier shot, a decoupling factor of ~ 300. Cowboy, as you know, gave a decoupling factor of ~ 120. Why the difference?

If we take these numbers seriously, and without new data I think we should, we ascribe the difference primarily to a medium effect for tamped explosions. The Cowboy decoupling factor, 120, is for a hole in salt relative to a tamped shot, also in salt. The factor 300 refers to a hole in salt relative to a tamped shot in Nevada tuff. The ratio $\frac{300}{120} \sim 2\frac{1}{2}$ is the decoupling factor for tamped explosions due to the change in medium. In other words a tamped explosion in tuff gives a seismic signal $\sim 2\frac{1}{2}$ times bigger than a tamped explosion of the same yield in salt.

It is true that the factor 300 is for nuclear explosions rather than the chemical explosions used in Cowboy. I doubt that the chemical-nuclear difference is significant, but insofar as it is, it probably works in the direction to require that the medium decoupling factor be even bigger than $\sim 2\frac{1}{2}$.

Further supporting the conclusion that there is a medium decoupling of $\sim 2\frac{1}{2}$ are the Cowboy measurements on the volume of cavities made by tamped explosions in salt as well as the measurement of the cavity volume produced by the Rainier explosion in tuff. These measurements indicate that the cavity volume is 2 or 3 times bigger in tuff than in salt for the same yield explosion. But the distant seismic signal is proportional to the cavity volume provided the medium is incompactible, which we believe to be the case for both salt and tuff. Therefore everything seems to hang together, except---the Russians have reported they set off a 700 ton HE shot in marble and obtained a distant seismic signal comparable to that from a 5 KT shot under Rainier conditions!

Marble, like salt, is a hard rock material with a high sound speed, and we would expect that if salt reduces the signal relative to tuff then marble would also reduce the signal relative to tuff. If we accept the statement of the Russians, then it is clear that we understand a good deal less than we thought we did, and not just about decoupling. It could be, for example, that marble behaves quite differently from salt or that the HE-nuclear difference in marble is much greater than we ever imagined. At this stage I personally do not accept the Russian statement because they have not given any confirmatory details, but I think an experiment should be made as soon as possible to check their result.

Sometimes we hear of experiments carried out by oil companies (so that the data are hard to get hold of), which apparently lead to the same conclusion as the Russian experiment. In these cases however, the signal turns out to have been measured not at the great distances which are

relevant to the Geneva Detection System (a thousand kilometers or so) but rather much closer to the point of the explosion (within a few kilometers), and here indeed one does expect that the signal from a hard rock medium will be bigger than the signal from a softer medium such as tuff. The reason is that at these closer distances the signal still consists mainly of high frequencies which have undergone considerable attenuation between source and receiver. The amount of this attenuation is a function of the Q-value of the medium and is generally less for the harder rock. Assuming the high frequency components to be roughly equal at the source, it follows that the (high frequency) signal at the receiver is greater in the hard rock medium than in the soft. On the other hand, when the receiver is at a great distance from the source, the signal consists only of low frequencies which have not been attenuated and whose amplitudes are larger, the softer the rock. In other words, for these experiments we can believe that the hard rock medium gives a bigger signal at close-in distances but a smaller signal at great seismic distances. This paradoxical situation remains to be verified by careful experiments.

I have discussed the magnitude of the decoupling factor. What about the volume of the cavity required to achieve this decoupling factor? The nominal volume that we specified in the Geneva talks for a spherical cavity in salt at a depth of about one kilometer is 7×10^4 cubic meters per kiloton. How sure are we of this number? The answer is, the number is very tentative because it is based almost entirely on theoretical considerations. We make the assumption that full decoupling will be obtained provided the medium responds elastically to the explosive forces,

which is a simple statement and certainly correct. However, the explosive forces produce a quite complicated pressure as a function of time on the cavity wall: a pressure spike roughly twenty times greater than the average pressure in the cavity, due to the reflection of the shock wave, followed by a more or less steady pressure which is equal to the average pressure in the cavity. The difficult problem is to decide, given this pressure as a function of time which acts on the cavity wall, whether the medium will be elastic. We are faced in this problem with all our uncertainties concerning the behavior of materials under dynamic loading. What we have done in the past at this point is to become very conservative.

I'll give just the gist of the argument. We say rock-like materials have little strength in tension and therefore the overburden pressure must be sufficient to keep the medium everywhere under compression throughout the explosion. For a medium such as salt, which creeps on a relatively short time scale compared to geologic times, the stress distribution around a spherical cavity is spherically symmetrical, and the hoop stress at the cavity wall is compressive and equal to three-halves times the overburden pressure, provided the radius of the cavity is small compared to its depth, and the depth is not so great that plastic flow occurs when the cavity is made. On the other hand the steady average pressure due to the explosion produces a hoop stress at the cavity wall which is tensile and equal to one-half the average pressure in the cavity, provided the medium remains elastic. It follows that to keep the medium in compression the average explosion pressure must be less than three times the overburden pressure.

Next we worry that this condition is not stringent enough because there could be cracks in the medium. Suppose a crack extends radially a considerable distance from the cavity and that the explosion gases leak into the crack and make a pressure equal to the average pressure in the cavity, which is what would happen if the cavity volume were large compared to the crack volume. Under these conditions, in order to ensure that the crack would not propagate, we must require that the average explosion pressure be less than the overburden pressure itself.

We have, of course, still to consider inelastic effects produced by the big pressure spike, both cracking and plastic flow of the medium. I won't go into detail, but as a result of these considerations we are led to an even more stringent condition on the volume of the cavity, namely, for cavities at a depth of about one kilometer, the average explosion pressure must not exceed one-half the overburden pressure, which incidentally fixes the nominal volume 7×10^4 cubic meters per kiloton. To get a better number, we need experiments.

You may ask what light Cowboy shed on the question of the minimum cavity volume for full decoupling. The answer, I'm afraid, so far as nuclear explosions are concerned, is very little. In the first place, Cowboy gave only a crude estimate of this quantity, but also Cowboy used chemical explosives which have much more impulse in the pressure spike than nuclear explosives of the same yield. Since in our theoretical considerations the minimum volume is set by the pressure spike, the Cowboy results are not very relevant.

Cowboy, however, did give us some new insight. Before Cowboy it was believed by some people that decoupling is an all-or-none effect. The analogy with a steam boiler was made to show that if the pressure exceeded some critical value the cavity would not contain the explosion. Cowboy showed, however, that decoupling is not an all-or-none effect but rather that the decoupling factor decreases in a gradual way as the explosion pressure is made greater than the overburden pressure.

Since decoupling decreases only gradually, we would like to have a curve of the decoupling factor as a function of volume, and we would like to have this curve for nuclear as well as chemical explosions. Cowboy showed that with chemical explosions the cavity volume could be made one-tenth of the nominal cavity volume and still there would be a salt-to-tuff decoupling factor of about thirty. What would the decoupling factor be with a nuclear explosive? Probably somewhat higher since the pressure spike is less severe--but again we need experiments.

There is something else we don't know. We don't know how to extrapolate the results of Cowboy to cavities at much greater depth. Cowboy, remember, was at a depth of ~ 250 meters, whereas the nominal cavity is at a depth of ~ 1 kilometer. The reason we cannot extrapolate straightforwardly is that at the greater depth plasticity plays an important role, which is not the case for Cowboy. To understand why, we recall that even in the most overdriven Cowboy experiment, the average explosion pressure was only five times the overburden pressure, which at the Cowboy depth means ~ 250 bars. This pressure is comparable to the yield stress of the medium and therefore plasticity plays no role or at most a minor one. However, for

the same degree of overdriving in a cavity at a depth of 1 kilometer, the average explosion pressure would be $\sim$1000 bars, which is many times greater than the yield stress of the medium. The question now becomes, which is worse from the point of view of decoupling, to have an elastic failure due to cracking, as was most probably the case for Cowboy, or an elastic failure due to plastic flow, as may be the case for cavities at greater depth?

We have done some theoretical work on this question which indicates that a little bit of plasticity is probably a good thing, and too much is a bad thing. How much is too much we don't really know, but we think for cavities at a depth of $\sim$1 kilometer that there is an advantage to plasticity over most of the range of overdriving in the Cowboy experiments. Such as it is, the theory suggests that with a cavity only one-tenth of the nominal volume the decoupling factor might be as much as 100 instead of the value 30 we have been quoting based on Cowboy. Not much more is likely to be learned about this subject, however, without some good experiments.

The RAND Corporation, Santa Monica, Calif.

RM-2659-ARPA

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS, by A. L. Latter; Research Memorandum RM-2659-ARPA, November 2, 1960, UNCLASSIFIED. 10 pp.

[illegible]

The RAND Corporation, Santa Monica, Calif.

RM-2659-ARPA

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS, by A. L. Latter; Research Memorandum RM-2659-ARPA, November 2, 1960, UNCLASSIFIED. 10 pp.

A discussion of the implications of, and questions raised by, the "Cowboy" underground detonations with chemical explosives. These experiments verified the correctness of the theory that explosions in a large cavity experience a "decoupling" effect, that is, the resulting seismic signals are muffled. The Cowboy tests left certain problems still to be solved (e.g., the relationship between cavity volume and depth and the decoupling factor, and the possibility that chemical explosions produce significantly different curves from nuclear explosions under the test conditions).

Presented before the VELA Technical Symposium at Washington, D. C., October 4-5, 1960.

The RAND Corporation, Santa Monica, Calif.

RM-2659-ARPA

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS, by A. L. Latter; Research Memorandum RM-2659-ARPA, November 2, 1960, UNCLASSIFIED. 10 pp.

A discussion of the implications of, and questions raised by, the "Cowboy" underground detonations with chemical explosives. These experiments verified the correctness of the theory that explosions in a large cavity experience a "decoupling" effect, that is, the resulting seismic signals are muffled. The Cowboy tests left certain problems still to be solved (e.g., the relationship between cavity volume and depth and the decoupling factor, and the possibility that chemical explosions produce significantly different curves from nuclear explosions under the test conditions).

Presented before the VELA Technical Symposium at Washington, D. C., October 4-5, 1960.

The RAND Corporation, Santa Monica, Calif.

RM-2659-ARPA

QUESTIONS FOR THE VELA PROGRAM ON DECOUPLING OF UNDERGROUND EXPLOSIONS, by A. L. Latter; Research Memorandum RM-2659-ARPA, November 2, 1960, UNCLASSIFIED. 10 pp.

A discussion of the implications of, and questions raised by, the "Cowboy" underground detonations with chemical explosives. These experiments verified the correctness of the theory that explosions in a large cavity experience a "decoupling" effect, that is, the resulting seismic signals are muffled. The Cowboy tests left certain problems still to be solved (e.g., the relationship between cavity volume and depth and the decoupling factor, and the possibility that chemical explosions produce significantly different curves from nuclear explosions under the test conditions).

Presented before the VELA Technical Symposium at Washington, D. C., October 4-5, 1960.